

# Evaluation of an Integrated Gas-Cooled Reactor Simulator and Brayton Turbine-Generator

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**Abstract** – A closed-loop brayton cycle, powered by a fission reactor, offers an attractive option for generating both planetary and in-space electric power. Non-nuclear testing of this type of system provides the opportunity to safely work out integration and system control challenges for a modest investment. Recognizing this potential, a team at Marshall Space Flight Center has evaluated the viability of integrating and testing an existing gas-cooled reactor simulator and a modified, commercially available, brayton turbine-generator. Since these two systems were developed independently of one another, this evaluation sought to determine if they could operate together at acceptable power levels, temperatures, and pressures. Thermal, fluid, and structural analyses show that this combined system can operate at acceptable power levels and temperatures. In addition, pressure drops across the reactor simulator, although higher than desired, are also viewed as acceptable. Three potential working fluids for the system were evaluated:  $N_2$ , He/Ar, and He/Xe. Other technical issues, such as electrical breakdown in the generator and the operation of the brayton foil bearings using various gas mixtures, were also investigated.

## I. INTRODUCTION

This paper provides an evaluation of the ability to integrate an existing gas-cooled reactor simulator and a modified, commercially available, brayton turbine-generator. Since these two systems were developed independently of one another, this evaluation had to determine if they could operate together at acceptable power levels, temperatures, and pressures. Provided the two systems could be operated together, this engineering evaluation also sought to determine the conditions that can be achieved during test. Three potential working fluids are evaluated:  $N_2$ , He/Ar, and He/Xe (results from  $N_2$ /He are also included as part of the analysis).

The paper begins with a general description of the existing hardware and facilities. A preliminary layout of a

closed-loop brayton cycle, incorporating this existing hardware, is then presented. This is followed by structural, flow, and heat transfer analyses of the gas-cooled reactor which must operate at much higher temperatures and flow rates than it was originally designed for. The predicted performance and output of the integrated system is presented. Finally, other technical concerns, such as electrical breakdown in the generator and the operation of the brayton foil bearings using various working fluids, are briefly addressed.

## II. DESCRIPTION OF EXISTING HARDWARE

The existing simulated gas-cooled reactor (called the Direct-Drive Gas-Cooled Reactor, or DDG) was developed

jointly by Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), and Marshall Space Flight Center (MSFC). The goal of this program was to design, build, and test a non-nuclear electrically-heated reactor core that simulates a nuclear system. The DDG was based on a gas-cooled, UN-fueled, pin-type fast reactor (37 heaters wired into six groups or zones). The DDG is shown in Fig. 1.

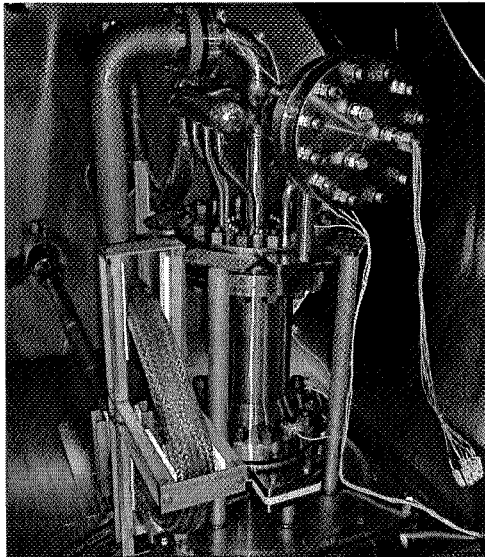


Fig. 1. DDG Assembly.

The DDG was designed to operate with a helium – argon gas mixture (80%/20% by volume) at 2413 kPa (350 psia), a core inlet temperature of 650 K, a core exit temperature of 850 K, and a bulk coolant flow of 0.1 kg/s. These design parameters were provided by LANL over 3 years ago and match the pressure conditions for a Jupiter Icy Moons Orbiter (JIMO) brayton at that time.

Nitrogen gas was used during preliminary testing in order to make the most efficient use of time and resources. DDG temperatures to 900 K at 620.6 kPa (90 psia) were demonstrated. A detailed description of the DDG hardware and testing is provided by Godfroy<sup>1</sup>.

The turbine-generator specified for this program is produced by Capstone Turbine Corporation. This off-the-shelf turbine-generator, designed to operate open-loop, would require modification for closed-loop operation. Capstone Turbine Corporation, located in Chatsworth, CA, is the world's leading producer of low-emissions microturbine power systems<sup>2</sup>. Capstone offers compact turbine generators for primary and emergency backup power. Their systems operate on a variety of liquid and gaseous fuels (e.g. propane, diesel, and natural gas) which, when mixed with air, are burned in a combustion chamber. The Capstone C30 microturbine is capable of generating

30 kW of electric power. The compressor, turbine, and magnet generator turn on a single shaft at high speeds. The radial flow turbine and single-stage centrifugal compressor operate on air bearings that require no additional lubricants, oils, or coolants. A cut-away view of the Capstone microturbine-generator is shown in Fig. 2.

At the time of this investigation, two options existed for obtaining a modified Capstone: 1) purchase a commercially available open-loop Capstone brayton and modify it for closed-loop operation, or 2) borrow an existing modified Capstone from Sandia National Laboratories.

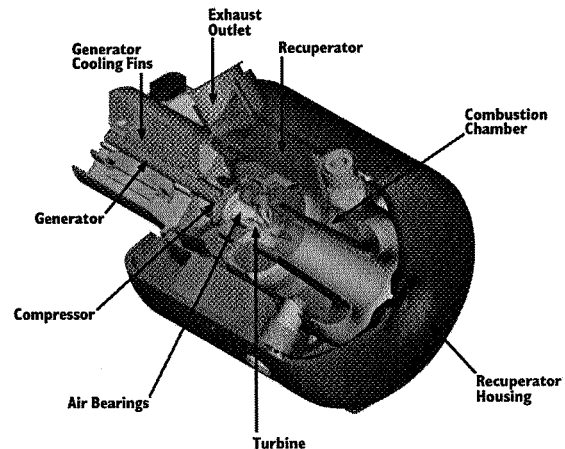


Fig. 2. Capstone Microturbine-Generator<sup>2</sup>.

Proposed testing of the integrated system would be conducted in a 9-ft by 18-ft vacuum chamber at MSFC's Early Flight Fission Test Facility (EFF-TF) (see Fig. 3). The chamber has sufficient volume to readily accommodate the DDG/brayton assembly. The chamber is equipped with internal rails to allow for easy installation of hardware that is mounted to portable tables.

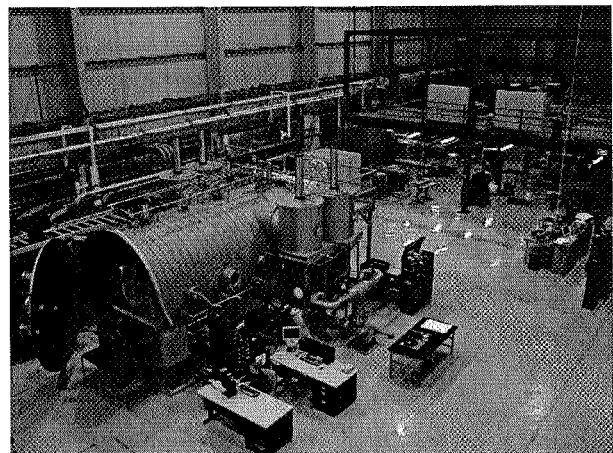


Fig. 3. EFF-TF Vacuum Chamber.

The chamber external walls are equipped with water/gas flow channels to provide cooling (to absorb high heat loads) or heating for general bake out of the chamber walls, critical to achieving low pressure levels and minimizing contamination of test articles.

### III. SYSTEM LAYOUT

The preliminary layout for the integrated DDG/brayton assembly is shown in Fig. 4. The assembly is shown installed in the 9 ft EFF-TF vacuum chamber. Arrows in the figure indicate the direction of flow through the system. The layout utilizes a new compact shell and coil chiller, support structures/tables, and flexible ductwork. A flowmeter is added to the assembly to measure gas flow through the loop (otherwise, flow rate must be calculated).

Flexible metallic hose was added to accommodate the thermal growth experienced by the high temperature ductwork. The digital power controller for the Capstone and controller for the DDG are located outside the chamber, and are therefore not shown.

### IV. SYSTEM EVALUATION AND ANALYSIS

This section presents detailed analyses of the integrated DDG and Capstone brayton. Since the two systems were developed independently of one another, these analyses were performed to determine if the two systems, when combined, could operate at acceptable power levels, temperatures, and pressures.

#### IV.A. DDG Structural Analysis

In order to evaluate overall system (brayton cycle) performance, the maximum allowable DDG operating temperature had to be determined. The DDG is constructed from both 316 and 316H stainless steel (316H has higher strength at elevated temperatures). Although 316 SS is able to withstand relatively high temperatures, it still limits the maximum operating temperature of the DDG. The ultimate temperature for the stainless steel DDG configuration requires a balance of temperature and pressure in order to meet structural limits

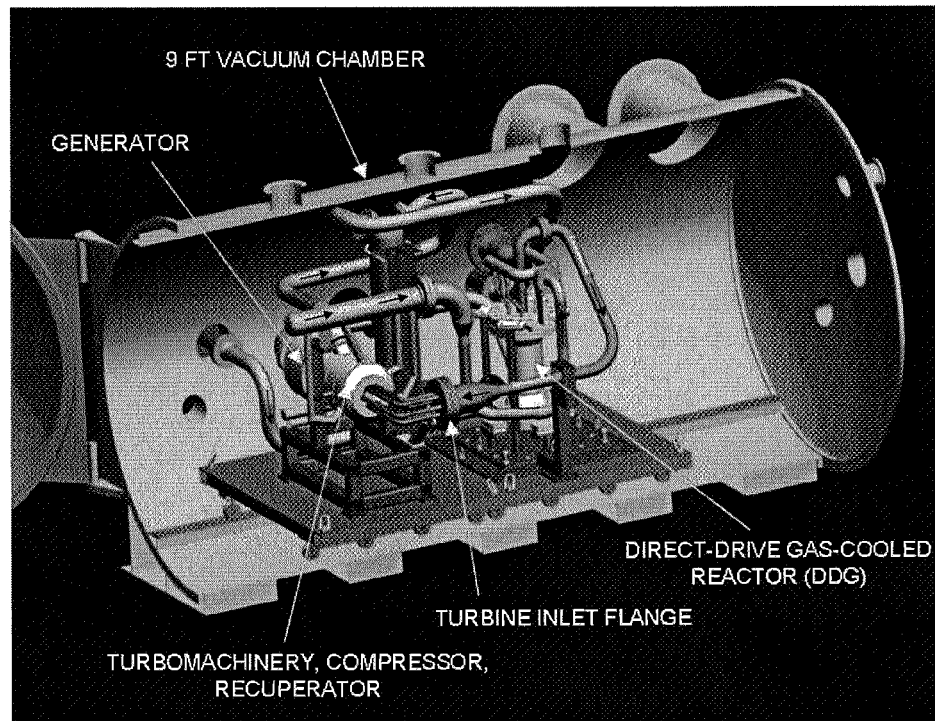


Fig. 4. Preliminary Layout for DDG/Brayton Cycle Testing.

The maximum inlet design pressure for the Capstone turbine inlet is 385 kPa (55.9 psia). The DDG, in contrast, was designed to operate at a much higher pressure 2414 kPa (350 psia). Therefore, the operating pressure for the DDG must be significantly dropped in order to operate with the Capstone brayton. At these lower pressures, the DDG can be operated at much higher temperatures.

The DDG vessel was evaluated for the following design conditions:

$$P = 365.4 \text{ kPa (53 psi)}$$

$$T = 1144 \text{ K (1600 °F)}$$

$$\text{Life} = 1000 \text{ hours}$$

$$\text{Working Fluid} = \text{Nitrogen}$$

$$\text{Ambient Environment} = \text{Nitrogen}$$

The design was evaluated using the ASME Boiler and Pressure Vessel Code rules. The code limits 316 SS piping to 1088 K (1500 °F). The evaluation done for 1144 K (1600 °F) uses the same rules but with design allowables extrapolated to the higher temperature. The low pressure, low thermal gradients, and slow thermal transients are not expected to introduce significant strains to limit life due to operational cycling. The limiting condition is creep due to the high temperature.

The results show that the DDG piping and flange components meet the requirements for the above design conditions. However, the current fasteners (grade B7 studs per ASTM A193 and grade 2H nuts per ASTM A194) cannot operate at 1144 K. To meet the 1000 hour life requirement, the fasteners must remain below 866 K. Although the fasteners will operate below 1144 K, replacement of the current fasteners is being considered. For example, A286 fasteners can operate at 983 K (1310 °F) for 1000 hours. Bolt temperatures will be monitored to ensure they do not exceed this temperature during operation.

#### IV.B. DDG Flow and Heat Transfer Analysis

With the maximum allowable DDG temperature defined, the next major step was to calculate the expected pressure drop,  $\Delta P$ , across the DDG during operation. Ideally, the  $\Delta P$  should remain below 3-5%; otherwise, the brayton cycle will experience a significant drop in performance (an ideal brayton cycle assumes that heat is added under constant pressure).

In addition to calculating pressure drop, the analyses sought to determine gas and clad temperatures, along with their sensitivities to inlet pressure, inlet temperature, and

power input. Pure nitrogen and helium, as well as various mixtures of the two, were examined in an attempt to find a suitable combination of gas, radial gap within the heater annulus, clad temperature, pressure drop, and gas temperature rise. Also examined were mixtures of He-Ar and He-Xe at mass fractions of He (0.13 for He-Ar and 0.05 for He-Xe) corresponding to minimum Prandtl numbers (0.37 for He-Ar and 0.20 for He-Xe). Of particular concern throughout the analyses was minimizing the pressure drop while keeping the outlet gas temperature and clad temperatures below acceptable structural limits. The analyses consisted of one-dimensional thermal/fluid networks, which were coded within the spreadsheet software, Microsoft Excel.

To validate the analysis models of the DDG, tests were conducted to measure pressure drop across the DDG. These tests, conducted at both room and elevated temperatures, compared the measured pressure drop with the pressure drop predicted by analysis. These tests were a valuable first step in validating the analysis.

All gases were treated as ideal for the determination of density,  $\rho$ . Approximating polynomials<sup>3,4</sup> were used to calculate the specific heat,  $C_p$ , thermal conductivity,  $k$ , and viscosity,  $\mu$ , of pure He, N<sub>2</sub>, Ar, and Xe. The specific heat of the binary gaseous mixture,  $C_{p,mix}$ , was calculated by

$$C_{p,mix} = mf_i C_{p,i} + (1-mf_i) C_{p,j}$$

where  $mf$  is the mass fraction and the subscripts  $i$  and  $j$  denote the individual gaseous components. The transport properties (i.e.,  $\mu_{mix}$  and  $k_{mix}$ ) for each of the gaseous mixtures are determined using the expressions<sup>5</sup>

$$\mu_{mix} = \frac{\sum_{i=1}^n \frac{x_i \mu_i}{\sum_{j=1}^n x_j \Phi_{ij}}}{\sum_{j=1}^n x_j \Phi_{ij}}$$

$$k_{mix} = \frac{\sum_{i=1}^n \frac{x_i k_i}{\sum_{j=1}^n x_j \Phi_{ij}}}{\sum_{j=1}^n x_j \Phi_{ij}}$$

where

$$\Phi_{ij} = \frac{1}{\sqrt{8}} \left( 1 + \frac{M_i}{M_j} \right)^{-1/2} \left[ 1 + \left( \frac{\mu_i}{\mu_j} \right)^{1/2} \left( \frac{M_j}{M_i} \right)^{1/4} \right]^2$$

Where  $n$  is the number of gaseous species in the mixture,  $x_i$  is the mole fractions of species  $i$ , and  $M_i$  is the molecular weight of species  $i$ . Table I gives calculated property values of all gases examined using the previous relations.

**Table I.** Gaseous properties at P=0.101 MPa.

Gas	T (K)	$\rho$ (kg/m <sup>3</sup> )	$C_p$ (J/kg.K)	$k$ (W/m.K)	$\mu$ (Pa.s)	Pr
Ar	300	1.623	520.3	0.0178	2.27E-05	0.66
	900	0.541	520.3	0.0405	5.17E-05	0.66
	1500	0.325	520.3	0.0572	7.30E-05	0.66
He	300	0.163	5193.2	0.1557	1.99E-05	0.66
	900	0.054	5193.2	0.3350	4.29E-05	0.66
	1500	0.033	5193.2	0.4845	6.21E-05	0.67
N <sub>2</sub>	300	1.138	1039.7	0.0261	1.79E-05	0.71
	900	0.379	1145.5	0.0597	3.88E-05	0.74
	1500	0.228	1243.8	0.0892	5.42E-05	0.76
Xe	300	5.333	158.3	0.0056	2.32E-05	0.66
	900	1.778	158.3	0.0143	6.01E-05	0.66
	1500	1.067	158.3	0.0208	8.72E-05	0.66
0.06He 0.94N <sub>2</sub>	300	0.837	1288.9	0.0470	1.88E-05	0.51
	900	0.279	1388.4	0.1044	4.07E-05	0.54
	1500	0.167	1480.7	0.1522	5.71E-05	0.56
0.10He 0.90N <sub>2</sub>	300	0.711	1455.0	0.0587	1.92E-05	0.48
	900	0.237	1550.3	0.1293	4.16E-05	0.50
	1500	0.142	1638.7	0.1874	5.85E-05	0.51
0.15He 0.85N <sub>2</sub>	300	0.599	1662.7	0.0712	1.96E-05	0.46
	900	0.200	1752.7	0.1560	4.24E-05	0.48
	1500	0.120	1836.2	0.2254	5.98E-05	0.49
0.13He 0.87Ar	300	0.749	1127.8	0.0724	2.38E-05	0.37
	900	0.250	1127.8	0.1599	5.33E-05	0.38
	1500	0.150	1127.8	0.2287	7.58E-05	0.37
0.05He 0.95Xe	300	2.059	410.1	0.0550	2.55E-05	0.19
	900	0.686	410.1	0.1295	6.38E-05	0.20
	1500	0.412	410.1	0.1875	9.25E-05	0.20

Following the approach given in Furukawa<sup>6</sup> the pressure drop,  $\Delta P$ , is determined by the relationship

$$\Delta P = f \frac{l}{d_h} \rho \frac{u^2}{2} \Gamma^m$$

where  $f$  is the friction factor,  $l$  is flow-path length,  $d_h$  is hydraulic diameter ( $d_h=d$  for a circular tube and  $d_h=d_o-d_i$  for a concentric annulus),  $u$  is the average fluid velocity, and  $\Gamma$  is the viscosity ratio defined as

$$\Gamma = \frac{\mu_b}{\mu_w}$$

where  $\mu$  is the fluid dynamic viscosity and the subscript,  $b$  or  $w$ , indicates that viscosity is evaluated at either the mean fluid bulk temperature or the mean wall temperature, respectively. A value of -0.25 is used for the exponent "m" throughout the analyses. For a circular tube the friction factor is calculated using the relations

$$f = \frac{64\psi}{Re} \quad \text{if } Re \leq 2000$$

$$f = 4 \{ 0.0522 - 0.0467(Re/1000) + 0.0156(Re/1000)^2 - 0.00164(Re/1000)^3 \} \quad \text{if } 2000 < Re < 4000$$

$$f = 0.3164Re^{-0.25} \quad \text{if } Re \geq 4000$$

For an annular cross-section formed by two concentric cylinders, the friction factor is determined by the relations

$$f = \frac{64\psi}{Re} \quad \text{if } Re < Re^*$$

$$f = 0.76 \varepsilon^{0.1} Re^{-0.25} \quad \text{if } Re \geq Re^*$$

where

$$\psi = \frac{(1-\varepsilon)^2}{[1+\varepsilon^2+(1-\varepsilon^2)/\ln\varepsilon]}$$

$$\varepsilon = \frac{d_i}{d_o}$$

$$Re^* = \frac{1250\psi^{1.33}}{\varepsilon^{0.133}}$$

A flow coefficient,  $K=f^*/d_h$ , of 0.5 is used at the inlet to sections of abrupt area change, and  $K=1$  is used at the outlets to account for the secondary pressure losses at those locations<sup>7</sup>. An effective length of 50 times  $d_h$  is used where the core annular flow turns around prior to entering the heater element annuli.

The only place where heat is exchanged in this model is through the annular heater flow passages. The equations used to calculate this exchange are<sup>8</sup>

$$h = \frac{\dot{q}}{\Delta T_{LM}}$$

$$\Delta T_{LM} = \frac{(T_w - T_{inlet}) - (T_w - T_{exit})}{\ln \left[ \frac{T_w - T_{inlet}}{T_w - T_{exit}} \right]}$$

For these analyses it is assumed that the specific heat capacity,  $C_p$ , of the fluid is sufficiently constant so that

$$T_{outlet} = T_{inlet} + \frac{\dot{Q}}{\dot{m} C_p}$$

For fully developed flow where the inner cylinder is heated and the outer cylinder is adiabatic

$$Nu = Nu_{lam} = 3.66 + 1.2 \varepsilon^{-0.8} \quad Re \leq 2300$$

$$Nu = \left( 1 - \frac{Re - 2300}{10^4 - 2300} \right) Nu_{lam,2300} + \left( \frac{Re - 2300}{10^4 - 2300} \right) Nu_{turb,10^4} \quad 2300 < Re < 10^4$$

$$Nu = Nu_{turb} = \frac{0.1075 \varepsilon^{-0.16} f_s Re Pr}{1 + 4.49 \sqrt{f_s} (Pr^{2/3} - 1)} \left[ 1 + \left( \frac{d_h}{L} \right)^{2/3} \right] \quad 10^4 \leq Re$$

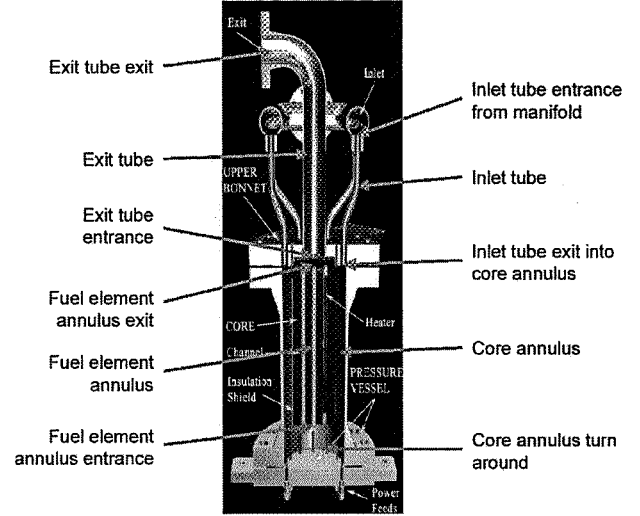
where

$$f_s = (1.8 \log_{10} Re - 1.5)^{-2}$$

The geometric definition of the analytical model is given in Table II and Figure 5. There are 6 inlet tubes and 37 fuel element annuli. The model assumes that the flow is distributed evenly. Therefore only one inlet tube and one fuel element annulus is modeled with  $1/6^{th}$  of the flow through the inlet tube,  $1/37^{th}$  of the flow through the element annulus, and  $1/37^{th}$  of the power input into the fuel element annulus.

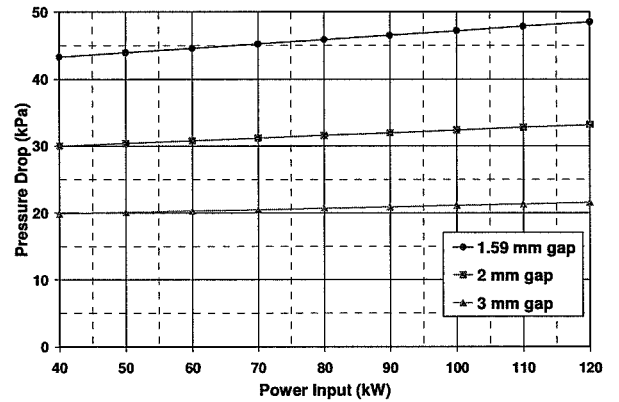
**Table II.** DDG Geometry Parameters.

	d or $d_i$ (m)	$d_2$ (m)	L (m)
Inlet tube	0.0236		0.4313
Core annulus	0.1778	0.2477	0.6775
Fuel element annulus	0.0159	0.0191	0.5271
Exit tube	0.0779		0.6314

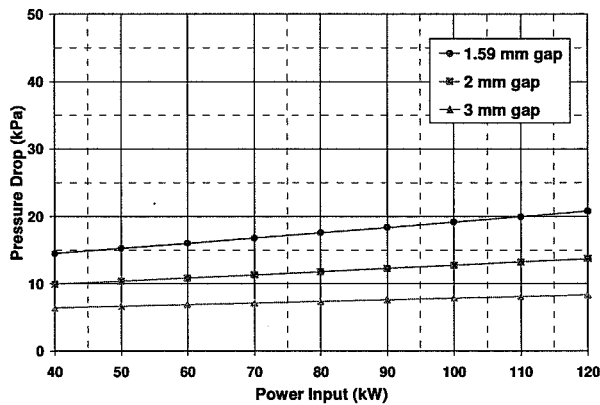


**Fig. 5.** DDG Geometry and Definition.

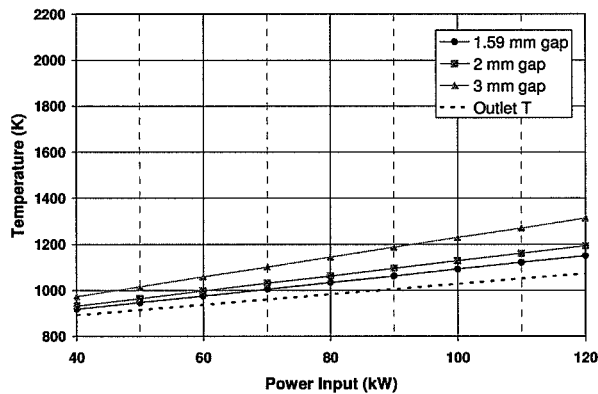
Over the course of this study many operating scenarios were examined. Figures 6 through 9 are representative of the data generated and the parameters varied. For each of these figures, the mass flow rate is 0.25 kg/s, the inlet pressure is 365.4 kPa, and the inlet temperature is 800 K.



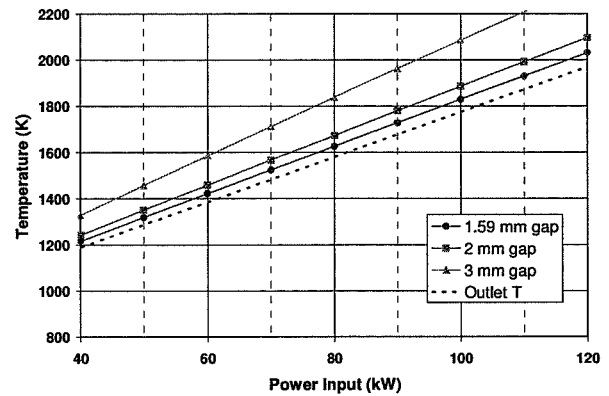
**Fig. 6.** Pressure drop versus power input for various gap widths where the fluid is 85% Nitrogen and 15% Helium, mass fraction.



**Fig. 7.** Pressure drop versus power input for various gap widths where the fluid is 95% Xenon and 5% Helium, mass fraction.



**Fig. 8.** Outlet gas and clad temp. versus power input for various gap widths where the fluid is 85% Nitrogen and 15% Helium, mass fraction.



**Fig. 9.** Outlet gas and clad temp. versus power input for various gap widths where the fluid is 95% Xenon and 5% Helium, mass fraction.

#### IV.C. Evaluation of Capstone Microturbine-Generator

Plots of the predicted performance for the DDG/Brayton assembly are shown in Figures 10 and 11. Both plots assume a constant turbine inlet temperature of 1044 K (1420 °F), a compressor inlet pressure of 101.4 kPa (14.7 psia), and a compressor inlet temperature of 288 K (59 °F). (Note: the compressor inlet conditions correspond to the International Standard Atmosphere (ISA) standard conditions). Flow rate versus RPM is shown in Figure 10. At a mass flow rate of 0.25 kg/s (0.55 lb/s), which is the mass flow rate assumed in the above analysis, the turbine speed is 85,000 RPM. This plot shows that shaft speed can be increased to 96,300 RPM (the rated speed of the Capstone), which results in a mass flow rate of 0.30 kg/s (0.66 lb/s).

RPM versus power output is shown in Figure 11. This figure shows the net electrical power generated at the output of the Capstone inverter. At 85,000 RPM, the Capstone will generate approximately 16.5 kW<sub>e</sub>. At 96,300 RPM, the Capstone will create approximately 24.0 kW<sub>e</sub>.

These plots account for the efficiencies of the turbine and compressor, efficiency of the generator and inverter, and pressure losses across the DDG, recuperator, and chiller.

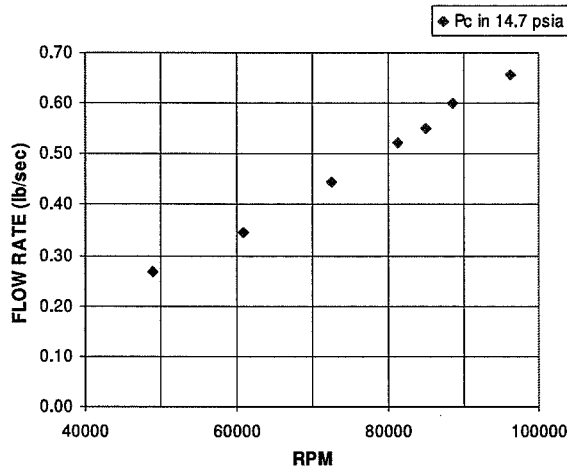


Fig. 10. Flow Rate vs RPM for DDG/Brayton Assembly.

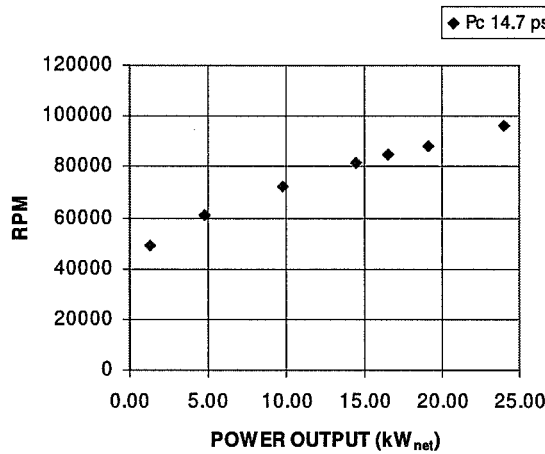


Fig. 11. RPM vs Power Output for DDG/Brayton Assembly.

Based on above results, the maximum electrical power (kW<sub>net</sub>) that can be generated using N<sub>2</sub> gas is 24.0 kW<sub>e</sub>. At this operating point, the following conditions exist in the system:

- turbine speed 96,300 RPM
- turbine inlet temperature 1044 K (1420 °F)
- flow rate 0.30 kg/sec (0.66 lb/s)
- thermal input (DDG) 99.4 kW<sub>t</sub>
- max DDG temperature 1141 K (1594 °F)
- comp. inlet pressure 101.4 kPa (14.7 psia)

- comp. discharge pressure 359.9 kPa (52.2 psia)
- ΔP across DDG 38.2 kPa (5.54 psi)
- overall system efficiency 24.1%

Except for pressure drop, these conditions meet the desired operating requirements and are within the operating limits of the DDG and Capstone microturbine. A pressure drop of 38.2 kPa (5.54 psi) is 11.8% of the turbine inlet pressure and exceeds the desired maximum pressure drop of 5%. Nevertheless, the brayton can still be operated at this higher pressure drop but at lower efficiencies. In addition, this pressure drop is for maximum flow rate through the system. At a lower mass flow rate, the percent pressure drop would decrease. For example, at 0.25 kg/s, the ΔP drops to 24.5 kPa (3.56 psi). For this assessment, it is assumed that the system is well insulated to prevent thermal losses which can have a dramatic impact on overall system performance.

Changes can be made to the flow passages of the DDG to lower this ΔP if desired. For example, by increasing the radial gap in the DDG from 1.59 mm to 2.0 mm, the ΔP can be decreased to 26.3 kPa (3.81 psi), or 8.1% of total.

In order to make a relative comparison between gas mixtures, the pressure drop for the different gas mixtures was calculated at the conditions shown above. These pressure drops are listed in Table 3.

**Table 3.** Pressure Drop Across DDG for Different Gas Mixtures, P<sub>in</sub> = 323.4 kPa (46.9 psia), T<sub>in</sub> = 743 K, mass flow 0.3 kg/s, power input = 99.4 kW

Gas	ΔP <sub>tot</sub> (kPa)	
	1.59 mm	2 mm
N <sub>2</sub>	38.2	26.3
0.94N <sub>2</sub> -0.06 He	50.9	35.0
0.9N <sub>2</sub> -0.1He	59.5	40.8
0.85N <sub>2</sub> -0.15He	70.4	48.2
0.13He-0.87Ar	59.0	40.3
0.05He-0.95Xe	27.0	18.1

#### IV.D. Assessment of Electrical Breakdown

Electrical breakdown of gases occurs as a result of collisions between electrons and gas molecules in the presence of an electric field<sup>9</sup>. Since the working gas for the closed-loop brayton cycle will permeate and cool the Capstone generator during operation, electrical breakdown must be considered. The Capstone generator was originally intended to operate on air at ambient



temperature and pressure, therefore, the use of other gases or gas mixtures may lead to electrical arcing.

Paschen curves for the different gases under consideration can be used to make a relative comparison of the breakdown voltages for the different gases. A Paschen curve defines the breakdown characteristics of a gas as a function (generally not linear) of gas pressure and gap length, i.e.  $V=f(pd)$ , for parallel-plane electrodes. In actuality, pressure should be replaced by gas density to account for the effect of temperature as well as pressure<sup>10</sup>. However, the breakdown voltage is also affected by other variables such as electrode material, electrode geometry, surface irregularities, and dust. Therefore, testing is often required to determine the breakdown voltages for a specific application and geometry.

The Paschen curves for several gases, including  $N_2$ , He, and Ar, are shown in Fig. 12<sup>9</sup>. Areas above the curve show when arcing will occur; areas below the curve show when arcing will not occur.

One area of potential arcing is between the generator's rotor and stator. Generally, this gap is minimized to improve generator efficiency. It is speculated that this gap could be as small as 0.08 cm (1/32 inch). If this is the case, then  $pd$  is 60.8 torr-cm when gas pressure equals 1 atmosphere (760 torr). Figure 12 can then be used to roughly approximate the voltage that electrical breakdown becomes a concern.

Since the working fluid may be a mixture of gases, the electrical breakdown of gas mixtures should also be addressed. Unfortunately, there is little data available on the electrical breakdown of gas mixtures and the infinite number of combinations that can result. However, there is data available that shows that the addition of small amounts of gas can have a dramatic effect on the Paschen curve of a pure gas.

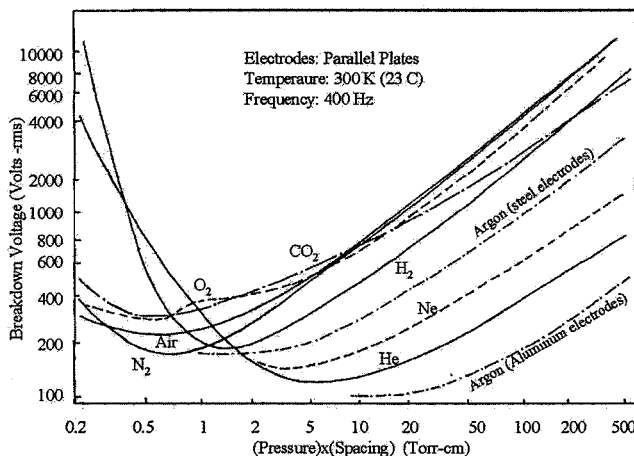


Fig. 12. Breakdown Voltage for Several Gases at Room Temperature<sup>9</sup>.

#### IV.E. Assessment of Capstone Foil Bearings

The Capstone microturbine/generator employs foil bearings for shaft support and axial thrust balance. Foil bearings create a wedged shaped geometry within the fluid. In principle when two surfaces form a wedge and one surface moves relative to the other, pressure is generated between the surfaces due to the hydrodynamic action of the fluid<sup>11</sup>. This pressure is used to support a load. In a foil journal bearing, a wedge is formed due to the eccentricity between the shaft center and the bearing center. Foil thrust bearings work on the same hydrodynamic principle as journal bearings; however the wedge shape is built into the bearing geometry.

Although many machines have been successfully run with working fluids other than air, such as helium, xenon, refrigerants, liquid oxygen, and liquid nitrogen, it is necessary to re-analyze the bearings for a change in working fluid. A change in gas or gas mixture with a different gas constant and a different viscosity will affect the load capacity, damping, and cooling (parasitic heat removal) of the bearings. The principle of a foil bearing is simple; however its analysis is not. The analysis requires simultaneous solutions or iterative methods to solve foil elasticity equations and fluid hydrodynamic equations<sup>11</sup>. It is suggested that such an analysis be implemented to verify that the journal and thrust bearings will perform satisfactorily with a working fluid other than air. This becomes especially important given that the Capstone foil bearings are designed with little margin in order to minimize bearing power losses.

#### V. CONCLUSIONS AND FUTURE WORK

Thermal, fluid, and structural analyses show that the DDG reactor simulator and a modified Capstone turbine-generator, when combined, can operate at acceptable power levels, temperatures, and pressures. Although pressure drops across the reactor simulator are higher than desired, they are viewed as acceptable. Changes can be made to the flow passages of the DDG to lower this pressure drop if desired.

Future work should include the development of a comprehensive systems model for the integrated system. An integrated model will most likely become too complex for the spreadsheet based approach used in these analyses. Therefore, a program such as GFSSP<sup>12</sup> (Generalized Fluid System Simulation Program) or PRC-SIM<sup>13</sup> is recommended for this systems model. PRC-SIM is a code developed by SNL for creating dynamic system models of reactor, power-conversion, and control systems.

Future work should also include a more detailed assessment of Capstone turbine and compressor for other gas mixtures. The evaluation in this report focused

primarily on nitrogen as the working fluid. He-Ar and He-Xe gas mixtures should be evaluated in greater detail.

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